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Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities

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ABSTRACT

Background: Extreme heat is a well-documented public health threat. The US National Weather Service (NWS) issues heat advisories and warnings (collectively, "heat alerts") in advance of forecast extreme heat events. The effectiveness of these alerts in preventing deaths remains largely unknown.
Objectives: To quantify the change in mortality rates associated with heat alerts in 20 US cities between 2001 and 2006.
Methods: Because NWS heat alerts are issued based on forecast weather and these forecasts are imperfect, in any given location there exists a set of days of similar observed heat index in which heat alerts have been issued for some days but not others. We used a case-crossover design and conditional logistic regression to compare mortality rates on days with versus without heat alerts among such eligible days, adjusting for maximum daily heat index and temporal factors. We combined city-specific estimates into a summary measure using standard random-effects meta-analytic techniques.
Results: Overall, NWS heat alerts were not associated with lower mortality rates (percent change in rate: −0.5% [95% CI: -2.8, 1.9]). In Philadelphia, heat alerts were associated with a 4.4% (95% CI: -8.3, −0.3) lower mortality rate or an estimated 45.1 (95% empirical CI: 3.1, 84.1) deaths averted per year if this association is assumed to be causal. No statistically significant beneficial association was observed in other individual cities.
Conclusions: Our results suggest that between 2001 and 2006, NWS heat alerts were not associated with lower mortality in most cities studied, potentially missing a valuable opportunity to avert a substantial number of heat-related deaths. These results highlight the need to better link alerts to effective communication and intervention strategies to reduce heat-related mortality.

1. Introduction

There is a well-established association between high ambient temperature (i.e., heat) and higher rates of mortality in the US and around the world (Anderson and Bell, 2009; Gasparrini et al., 2015; Guo et al., 2014; Medina-Ramon and Schwartz, 2007). Globally, the public health burden of exposure to heat is substantial. In the United States (US), a recent analysis found that 0.35% (95% CI: 0.30, 0.39) of the approximately 22 million deaths that occurred in 135 communities between 1985 and 2006 were attributable to heat (Gasparrini et al., 2015), or approximately 3642 deaths per year.

The growing recognition of the dangers of heat has prompted communities around the world to develop heat early warning systems to provide advance notice to public health and emergency management officials, as well as to the general public, when a period of dangerous heat is forecast to occur (Lowe et al., 2011). In the US, in an effort to mitigate the harmful impacts of heat on health, local offices of the US National Weather Service (NWS) issue heat alerts in advance of forecast extreme heat events. These alerts are communicated to the public through local media outlets and currently contain recommendations that members of the public can use to protect their health, such as wearing light-colored clothing and drinking plenty of water. In addition, NWS heat alerts may trigger a cascade of local interventions aimed at protecting the public from the health impacts of heat. For example, heat alerts may activate elements of local heat response plans, such as additional messaging or the opening of cooling centers (Arizona Department of Health Services, 2016; Sheridan and Kalkstein, 2004; Wisconsin Climate and Health Program, 2016). While heat alerts are

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Fig. 1. US cities included in this study.

expected to be an important tool for communicating risk and preventing deaths during extreme heat events, the evidence regarding whether such alerts yield measurable health benefits is sparse (Benmarhnia et al., 2016; Chau et al., 2009; Ebi et al., 2004; Toloo et al., 2013).

Local offices of the NWS typically issue heat alerts based on forecasts of the heat index, a measure of human discomfort that incorporates both temperature and relative humidity. Current guidance at the national level suggests issuing a heat advisory (a heat alert issued when less extreme heat is forecast) when the heat index is expected to meet or exceed 100 °F (northern US) or 105 °F (southern US), and an excessive heat warning (a heat alert issued when more extreme heat is forecast) when the heat index is expected to meet or exceed 105 °F (northern US) or 110 °F (southern US). These criteria are provided as guidelines to each of the 122 local NWS offices and may be adapted to local needs (Hawkins et al., 2017).

While the exact criteria used to issue heat alerts varies across the jurisdictions of local NWS offices, a key commonality across jurisdictions is that heat alerts are issued based on *forecasts* of future weather conditions. Furthermore, in addition to using information from forecast models, NWS forecasters are encouraged to use their experience and judgment in making the decision to issue a heat alert (Hawkins et al., 2017). Because forecasts do not perfectly predict observed temperatures (Zhang et al., 2014; Åström et al., 2015) and NWS forecasters are encouraged to use their judgment instead of adhering strictly to any criteria, heat alerts are sometimes issued for days that turn out to have an observed heat index below the regional guidelines described above. For example, in a city where heat advisories are issued when the heat index is forecast to exceed 100 °F, a heat alert would likely be issued for a day that is forecast to be 101 °F, yet it is possible for the heat index actually observed on that day to be slightly below 100 °F due to uncertainty in the forecast. Similarly, heat alerts are sometimes not issued for days that turn out to have an observed heat index above the regional guidelines (Vargo et al., 2015; Zhang et al., 2014). Thus, in each city for which heat alerts are issued, there exists a set of days with approximately equal observed maximum daily heat index, some of which have heat alerts and some of which do not. This data structure allows us to ask whether, among days of approximately equal observed heat index, the daily mortality rate is lower on days for which a heat alert was issued compared to days for which a heat alert was not issued. In other words, due to forecast uncertainty we are able to estimate the association between heat alerts and mortality while conceptually controlling for the influence of observed heat index through matching.

We used this natural experiment to evaluate whether NWS heat alerts were associated with lower rates of mortality across 20 US cities between 2001 and 2006. This analysis rests on the assumption that in any given location, two days of approximately equal observed heat index – one with a heat alert and one without a heat alert – will have the same rates of mortality except due to the effect of the heat alert, after controlling for any potential confounders. In secondary analyses we explored whether city-level characteristics, such as air conditioning (AC) prevalence and population characteristics, are associated with the effectiveness of heat alerts in preventing mortality. Additionally, we estimated the number of deaths actually and potentially averted by heat alerts in these 20 cities between 2001 and 2006, assuming that the observed associations were causal.

2. Methods

2.1. Study sites

To evaluate the effectiveness of heat alerts we linked daily data on heat alerts (available starting in 2001) with daily mortality data (available through 2006). We selected for analysis the 20 US cities for which local offices of the NWS issued the largest number of heat alerts between 2001 and 2006 and on which we could obtain daily mortality data (Fig. 1).

2.2. Data sources

2.2.1. Heat alerts

We obtained text files of all NWS non-precipitation products (the technical term for NWS messaging) issued in the US between April 1st and October 31st during the years 2001 to 2006 from the National Oceanic and Atmospheric Administration (NOAA) (NOAA, 2016). We developed a text parsing program to separate heat alerts from other types of messaging and to extract information on the location and date of each heat alert. We defined “heat alerts” as including both heat advisories (a type of heat alert issued when less severe heat is forecast) and excessive heat warnings (a type of heat alert issued when more severe heat is forecast). We assessed the performance of this program in a subset of nine cities by comparing program-generated results to results generated by manually reading the contents of each alert text file and recording the dates and locations of all heat alerts. We found that

our program extracts the dates on which heat alerts were in effect with minimal difference compared to the more labor-intensive process of extracting information from NWS's text records by hand. Specifically, across the nine test cities our program identified 97.6% of those days manually identified as having a heat alert, and identified 100% of days manually identified as having no heat alert.

As heat alerts are issued for NWS-delineated forecast zones rather than for individual cities, we identified the forecast zone within which each of the 20 study cities is located and used our text parsing program to reconstruct a time series of heat alerts for that zone. For cities spanning more than one forecast zone, we constructed the time series using the zone encompassing the largest proportion of each city's population (see Table S1). Records of heat alerts in 2001 were not available in Bakersfield, CA or Phoenix, AZ; thus, we restricted the analysis in these two cities to the period of 2002 to 2006.

2.2.2. Heat index

We obtained hourly observations of temperature and dew point measured at airport weather stations from NOAA (NOAA, 2017) and calculated daily maximum heat index values for each city using an algorithm developed by the NWS (NWS, 2014). Compared to other methods for calculating the heat index, this algorithm is the most consistent with the theoretical concept of apparent temperature (Anderson et al., 2013). The airport weather station used in each city is listed in Table S1.

2.2.3. Mortality

We obtained data on death records for each of the 20 cities between 2001 and 2006 from the US National Center for Health Statistics. From these records, we constructed time series of daily counts of non-external deaths (all ICD-10 codes except for V01-Y98) in each city. We defined cities as the county or set of counties in which the city is located (see Table S1). We elected to construct these city-level time series using deaths coded as being due to any non-external cause as opposed to only those deaths coded as being due to heat, as the latter are thought to comprise only a fraction of the total impact of heat on mortality (Berko et al., 2014).

2.2.4. City-level characteristics

We estimated air conditioning (AC) prevalence in each city using data from the American Housing Survey (AHS), which is conducted biennially in a rotating set of 41 metropolitan areas. As the set of metropolitan areas included in the survey varies from year to year, we estimated AC prevalence for the temporal midpoint of our study (2004) in each metropolitan area through linear interpolation of survey data over a 20-year period (1994–2013) (Nordio et al., 2015). For each city, we assigned the estimated 2004 AC prevalence from the closest participating metropolitan area. We used city-level estimates from the 2000 U.S Census to determine the percent of residents 65 years of age or older in each city.

2.3. Statistical analysis

We estimated the association between heat alerts and mortality in each city using a case-crossover approach, a study design appropriate for quantifying the association between transient exposures and acute outcomes such as death (Maclure, 1991). In the case-crossover design, an individual's exposure immediately before the outcome occurs (i.e., the “case period”) is compared to their exposure during at least one window of time during which the outcome did not occur (i.e., the “control period”). As our main analysis, we defined the outcome as death and the exposure as whether or not a heat alert was issued. To meet the assumption of positivity, we restricted the analysis to those days (hereafter referred to as “eligible days”) on which the observed daily maximum heat index in each city was high enough that a heat alert during this time period could plausibly have been issued, but not so high that the probability of a heat alert being issued was 100%. Specifically, we defined the lower bound of eligibility as the lowest value of daily maximum heat index at which a heat alert was issued in a given city, minus an additional 2 °F, and defined the upper bound of eligibility as the highest value of daily maximum heat index at which no heat alert was issued, plus an additional 2 °F (see Table 2).

For each death occurring on an eligible day, we defined the case period as the day on which the death occurred, and defined its corresponding control periods as all other eligible days within the study period occurring in the same calendar month as the case period. We then modeled the association between heat alerts and mortality using conditional logistic regression models, adjusting for daily maximum heat index (using a linear and quadratic term), calendar year, day of week, and federal holidays. We present associations for each city individually, quantified as the percent difference in the rate of death comparing days with versus without heat alerts. We also present a random-effects meta-analytic summary estimate of the association across all 20 cities.

In sensitivity analyses, we evaluated the association between heat alerts and mortality when: (1) additionally controlling for daily maximum heat index and the presence or absence of a heat alert on the two days prior to the index day; (2) restricting the exposure to excessive heat warnings only (rather than the combined measure of excessive heat warnings and heat advisories) in a subset of six cities that issued excessive heat warnings frequently, as local interventions triggered by heat alerts may vary depending on the type of alert issued (Kalkstein et al., 2009); and (3) excluding the small set of heat alerts that were issued based on forecast high heat index, but were subsequently cancelled due to a changing forecast. Additionally, we explored whether heat alert effectiveness varies depending on timing within the season by stratifying the analysis by whether they occurred early (April through July) or late (August through October) in the season. These analyses are further described in the Supplemental Material.

We applied meta-regression models (Berkey et al., 1995) to identify whether the following four city-level characteristics explained variability in heat alert effectiveness across cities: city-specific observed mean value of maximum daily heat index between April and October, AC prevalence, percent of the population age 65 years and older, and the percent of heat alerts issued as excessive heat warnings rather than heat advisories. We constructed this fourth characteristic in order to examine the impact of excessive heat warnings, the more severe form of heat alert, even in cities that issue them infrequently. We weighted the estimate of each city's heat alert effectiveness by its inverse variance, and included each city-level characteristic in the model individually. Additionally, because the distribution of heat index values on eligible days varied in terms of both the range and center, we investigated whether heat alert effectiveness varied as a function of these two characteristics. Specifically, we applied additional meta-regression models using as predictors: (1) the heat index range on eligible days in each city, calculated by subtracting the lower boundary of the range from the upper boundary of the range, and (2) the percentile of each city's distribution of daily maximum heat index at which the median value of the eligible day range falls.

When study subjects share a common exposure (e.g., heat alerts issued for the population of a city), the case-crossover design is equivalent to a time series analysis carried out using a log-linear model with a Poisson distribution (Lu and Zeger, 2007). While we originally conceived of this study as a case-crossover analysis, we also built the equivalent log-linear time series model for each city. These models, which under the stated conditions yield identical rate ratios for the association between heat alerts and mortality as those in the case-crossover analysis, were restricted to the set of eligible days described above, and were controlled for year, month, day of week, federal holidays, and daily maximum heat index. From these models, we calculated the number of deaths averted per heat alert in cities in which we observed a statistically significant reduction in the mortality rate

comparing days with and without heat alerts, as follows:

$$D_x = n_x * (1 - RR_x)$$

where D_x is the number of deaths averted in city x; RR_x is the incidence rate ratio for the association between heat alerts and mortality in city x; and n_x is the expected number of deaths on a day on which the maximum heat index is equal to the median heat index on days on which heat alerts were issued in city x, the year is 2003, the month is July, the day of week is Wednesday, and the day is not a holiday. The quantity $(1 - RR_x)$ is the preventable fraction, or the fraction of the death rate that could be prevented by heat alerts assuming the observed association is causal, and is conceptually similar to the attributable fraction calculated for exposures with an RR greater than one. We additionally calculated the mean number of deaths averted per year given a city's observed heat alert history by multiplying D_x by the mean number of alerts issued per year on eligible days in city x.

To quantify the uncertainty in our estimates of deaths averted per heat alert and per year, we drew 5000 random samples from a normal distribution constructed from the point estimate for $\log(RR_x)$ and its standard error. We then calculated the number of deaths avoided per heat alert and per year for each sample in the distribution of $\log(RR_x)$, thus constructing distributions of those two quantities. Finally, we estimated 95% empirical confidence intervals (eCI) for the number of deaths avoided per heat alert and per year by taking the 2.5th and 97.5th percentiles of their distributions.

As Philadelphia was the only city in which we observed a statistically significant reduction in mortality associated with heat alerts, we conducted a post hoc analysis in which we estimated the potential number of deaths that could have been averted (per heat alert and per year) in each of the remaining 19 cities, under the counterfactual scenario that heat alerts in these cities had been associated with the same reduction in mortality as observed in Philadelphia. This post hoc analysis assumes that (1) the protective association we observed in Philadelphia is causal, (2) the association in Philadelphia is attributable to the way in which the local NWS, local government agencies, and the general public communicate about and respond to heat alerts, and (3) the actions undertaken in Philadelphia to achieve this response could be applied in other cities, such that the benefit observed in Philadelphia could be realized elsewhere. This analysis is intended as a thought experiment to estimate the potential benefit of heat alerts on mortality in each city under the above assumptions. To obtain this estimate, we repeated the calculation of D_x described above for each city, replacing RR_x with the rate ratio observed in Philadelphia.

All statistical analyses were carried out in R version 3.3.1 and Stata version 14.0. The text parsing program was developed in Python version 2.7.10. A two-sided p-value of < 0.05 was considered statistically significant.

3. Results

Across all 20 cities during April–October of 2001–2006, the average maximum daily heat index ranged from 75 °F (New York, NY) to 94 °F (Phoenix), and mean daily mortality ranged from 3 deaths per day (Monroe, LA) to 140 deaths per day (New York). Fayetteville, NC issued the fewest heat alerts (4.8 alerts per year) while Phoenix issued the most (12.4 alerts per year) (Table 1). In most cities, heat advisories were more common than excessive heat warnings.

The range of observed values of maximum daily heat index on eligible days (defined as those days when the probability of an alert being issued is > 0, but < 1) varied across cities. Eligible days tended to span lower values of heat index in Northern versus Southern cities. For example, in Philadelphia, PA, the lowest maximum daily heat index at which a heat alert was issued was 92 °F and the highest value of heat index at which no alert was issued was 103 °F. Thus, our analyses for Philadelphia was restricted to days with a heat index between 90 and 105 °F. In contrast, in Phoenix our analyses were restricted to days with a maximum heat index between 95 and 113 °F. However, there was variability in this range even between some cities in close geographic proximity and with similar climates, potentially because some such cities fall under the jurisdiction of local NWS offices that use different criteria to issue heat alerts. The mean annual number of days eligible for inclusion in our analysis in each city ranged from 24 (Wilmington, DE) to 115 (Phoenix), and the percent of eligible days on which a heat alert was actually issued ranged from 6% (Fayetteville) to 34% (Kansas City, KS and Wilmington) (Table 2).

Table 1
Characteristics of US cities included in this study by region during April through October 2001–2006.

City	Mean (1st-99th percentile) daily maximum heat index [°F]	Mean number of heat alerts issued per year [n/year]	Mean daily mortality [n/day]
Midwest			
Kansas City, KS	81 (45, 113)	11.5	27
Topeka, KS	82 (46, 113)	7.0	4
Northeast			
Baltimore, MD	78 (46, 105)	10.7	36
New York, NY	75 (43, 103)	6.2	140
Philadelphia, PA	77 (47, 104)	10.7	105
Rockville, MD	79 (47, 106)	10.2	12
Trenton, NJ	76 (44, 103)	10.7	7
Upper Marlboro, MD	79 (47, 106)	10.2	10
Washington, DC	79 (47, 106)	10.7	14
Wilmington, DE	76 (45, 102)	10.5	10
Southeast			
Annandale, VA	79 (47, 106)	10.2	10
Charleston, SC	88 (62, 111)	6.0	7
Fayetteville, NC	84 (56, 105)	4.8	5
Little Rock, AR	87 (57, 109)	10.2	8
Memphis, TN	86 (58, 107)	6.5	18
Monroe, LA	89 (62, 108)	7.5	3
Southwest			
Dallas/Fort Worth, TX	90 (62, 107)	11.8	56
Tulsa, OK	87 (55, 112)	8.5	12
Phoenix, AZ[a]	94 (72, 110)	12.4	56
West			
Bakersfield, CA[a]	87 (61, 110)	5.8	13

[a] 2002 to 2006 only.

In each city, estimated the association between heat alerts and mortality on these eligible days. The association between heat alerts and mortality in individual cities varied in terms of sign, magnitude, and precision (Fig. 2). In Philadelphia, a larger city with relatively more heat alerts, heat alerts were associated with a 4.4% lower [95% CI: −8.3, −0.3] mortality rate, suggesting a protective effect of heat alerts on mortality. However, in other cities with similarly precise estimates – such as Phoenix, New York, and Dallas/Fort Worth, TX – the association between heat alerts and mortality was indistinguishable from the null hypothesis of no association. Considering all 20 cities together in a random effects meta-analysis, we did not find evidence of a statistically significant association between heat alerts and mortality during the study years (summary percent change in the rate of death: −0.5% [95% CI: -2.8, 1.9]), although there was evidence of heterogeneity across cities (p-value for heterogeneity: 0.08). Results from fixed-effects meta-analysis were similar to those from the random effects model (summary percent change in the rate of death: -0.8 [95% CI: -2.4, 0.9]).

The meta-analytic summary estimate remained largely unchanged in sensitivity analyses (Table S2). Specifically, our results were not materially different when we controlled for maximum heat index and the presence or absence of a heat alert on the two days leading up to the case day, nor when we restricted the analysis to the most severe form of heat alerts (i.e., excessive heat warnings) or to those heat alerts that were not subsequently cancelled. Considering all 20 cities together in

Table 2
Characteristics of days included (i.e., eligible days) in the case-crossover analysis in each city.

City	Lowest heat index on a day on which an alert was issued [˚F]	Median heat index on days on which alerts were issued [˚F]	Highest heat index on a day on which no alert was issued [˚F]	Heat index range used to determine eligible days[a] [˚F]	Mean annual number of eligible days [days/year]	Percent of eligible days with a heat alert [%]
Midwest						
Kansas City, KS	99	109	116	97–118	34.2	34
Topeka, KS	103	110	117	101–119	24.5	29
Northeast						
Baltimore, MD	91	100	103	89–105	41.8	22
New York, NY	91	101	101	89–103	30.3	14
Philadelphia, PA	92	101	103	90–105	35.7	26
Rockville, MD	95	102	107	93–109	29.8	30
Trenton, NJ	91	99	103	89–105	37.5	25
Upper Marlboro, MD	95	102	107	93–109	29.8	30
Washington, DC	92	102	113	90–115	45.3	23
Wilmington, DE	93	99	99	91–101	23.5	34
Southeast						
Annandale, VA	95	102	107	93–109	29.8	30
Charleston, SC	100	106	114	98–116	48.0	13
Fayetteville, NC	91	105	110	89–112	79.7	6
Little Rock, AR	99	106	110	97–112	50.3	20
Memphis, TN	100	105	111	98–113	38.8	17
Monroe, LA	98	105	112	96–114	72.5	10
Southwest						
Dallas/Fort Worth, TX	95	104	112	93–114	96.2	12
Tulsa, OK	101	106	115	99–117	44.0	19
Phoenix, AZ	97	105	111	95–113	115.4	11
West						
Bakersfield, CA	97	106	116	95–118	54.4	10

[a] Range of values of daily maximum heat index used to determine which days are included in the case-crossover analysis. In each city, the lower bound of this range is defined as the lowest value of daily maximum heat index on days which a heat alert was issued (column 2), minus 2 ˚F. The upper bound is defined as the highest value of daily maximum heat index on days on which no heat alert was issued (column 4), plus an additional 2 ˚F.

stratified analysis, we estimated a percent change in the rate of death of 0.1% [95% CI: -2.8, 3.1) during April through July, but of −2.8% [95% CI: -6.0, 0.5] during August through October (Table S3). However, considering each city individually, there was not a consistent trend towards larger reductions in the mortality rate on heat alert days issued in August through October.

In second-stage meta-regression models, the effectiveness of heat alerts was not associated with mean daily maximum heat index, AC prevalence, percent of the population aged 65 years or older, or the percent of heat alerts issued as excessive heat warnings rather than heat advisories (Fig. 3). Additionally, heat alert effectiveness was not associated with either the size of the eligible day range or with the percentile of city-specific heat index distribution at which the median value of the eligible day range falls (data not shown).

In Philadelphia, approximately 111 deaths are expected on a typical eligible July day without a heat alert (and on which other covariates are set equal to the values specified in the Methods section). Assuming the association between NWS heat alert and reduced mortality we observed in Philadelphia is causal, we estimate that between 2001 and 2006, on average, 4.8 (95% eCI: 0.3, 9.1) deaths were averted each time a heat alert was issued in Philadelphia. We further estimate that conditional on the observed history of heat alerts during this time period, heat alerts on eligible days averted 45.1 (95% eCI: 3.1, 84.1) deaths per year in Philadelphia (Table 3).

As noted above, heat alerts in other cities were not found to be statistically significantly associated with lower mortality rates. We estimated the potential number of deaths that might have been averted in these 19 cities under the counterfactual scenario that heat alerts in these cities had been associated with the same reduction in mortality as observed in Philadelphia and assuming that the association we observed in Philadelphia is causal. This analysis is intended as a thought experiment to estimate the potential benefit of heat alerts on mortality in each city under the above assumptions. Conditional on the observed history of heat alerts in each of the remaining 19 cities between 2001 and 2006, we estimate that the number of deaths that could have been potentially averted in each city under the above assumptions ranged from 1.0 (95% eCI: 0.1, 1.8) deaths per year in Monroe to 28.2 (95% eCI: 1.9, 52.6) deaths per year in Dallas/Fort Worth (Table 3).

4. Discussion

There is an abundance of evidence linking exposure to extreme heat to both fatal (Anderson and Bell, 2009; Gasparrini et al., 2015; Guo et al., 2014; Medina-Ramon and Schwartz, 2007) and non-fatal (Bobb et al., 2014; Gronlund et al., 2014; Kingsley et al., 2016; Lin et al., 2009; Wellenius et al., 2017) health outcomes. Because they provide US communities information in advance of forecast extreme heat, NWS heat alerts are a key driver of the public health response to heat. However, we found that between 2001 and 2006, heat alerts across 20 US cities were not associated with statistically significant lower mortality rates, suggesting that the full public health potential of heat alerts has yet to be realized. As we discuss in more depth below, these results were obtained from a specific set of years (2001 to 2006), cities, and days (those within a narrow range of observed heat index) and may not be generalizable to more recent years, to other locations, or to days on which the observed heat index is very high.

A number of previous studies have found that the association between heat and mortality is attenuated following the implementation of a heat alert system (Fouillet et al., 2008; Heudorf and Schade, 2014; Morabito et al., 2012; Nitschke et al., 2016; Palecki et al., 2001; Schifano et al., 2012; Tan et al., 2007). For example, Fouillet et al. found that there were approximately 4400 fewer observed excess deaths during a 2006 heat wave in France than were expected given the characteristics of the heat wave, a finding which the authors suggested may have been due to the implementation of adaptive measures including a heat early warning system following the severe European heat

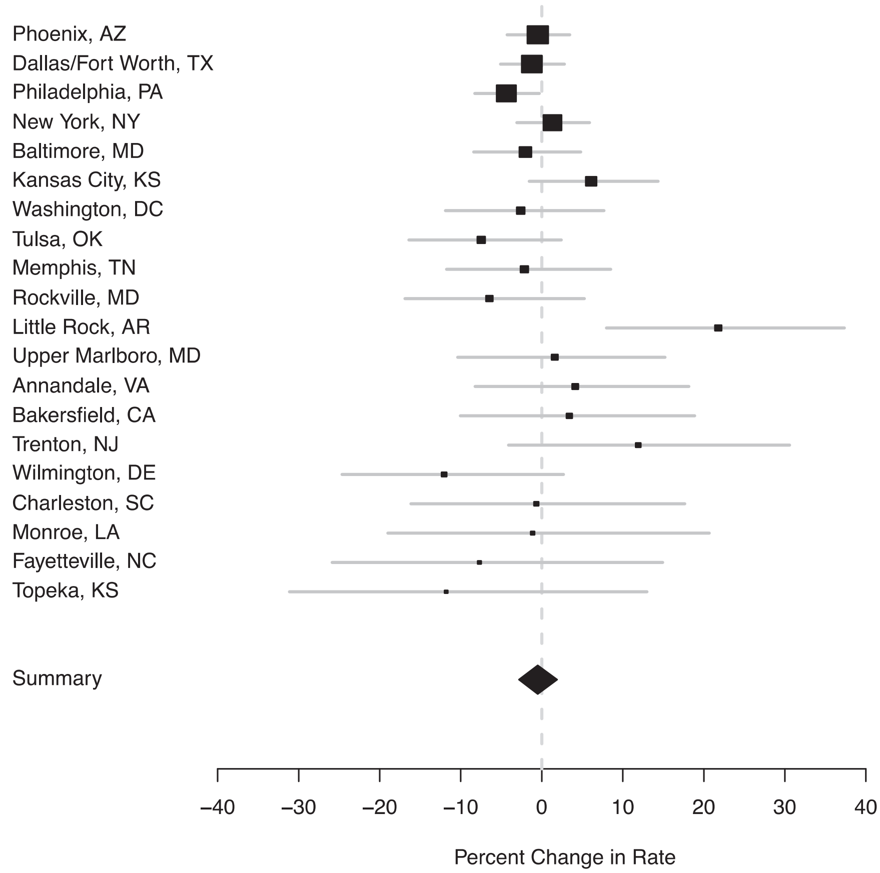

Fig. 2. Percent change (and 95% confidence interval) in the rate of death comparing days with versus without National Weather Service heat alerts in 20 US cities, 2001–2006.

wave of 2003 (Fouillet et al., 2008). However, these prior studies have all been pre/post analyses in which factors that change over time other than the implementation of a heat early warning system may account for the results. These factors could include other community-level or individual-level measures aimed at preventing heat-related mortality, increased awareness of the dangers of heat, increased use of air conditioning, and changes in baseline health status over time.

Our study addresses a different question: does issuing an NWS heat advisory or excessive heat warning prevent excess deaths? Only three published studies have looked specifically at this question. First, in Philadelphia, each heat alert issued between 1995 and 1998 was associated with an estimated 2.6 (95% CI: -1.0, 6.1) fewer deaths among those aged 65 years and older (Ebi et al., 2004). This is similar to our estimate for Philadelphia that a heat alert was associated with 4.8 (95% CI: 0.3, 9.0) fewer all-ages deaths per heat alert between 2001 and 2006. Second, in Montreal, an estimated 2.5 (95% CI: -0.3, 5.4) all-ages deaths were avoided on each day that was hot enough to trigger an alert between 2004 and 2007 (Benmarhnia et al., 2016). Finally, on each day *without* a heat alert, there were an estimated 1.2 (95% CI: 0.3, 2.1) additional deaths from ischemic heart disease and 1.0 (95% CI: 0.0, 1.9) additional deaths from stroke among adults 65 years and older in Hong Kong between 1997 and 2005. Collectively, these studies suggest a protective association between heat alerts and mortality, although it is possible that null findings from other cities or time periods may not have reached the academic literature due to publication bias. Additionally, these studies have been limited to single locations and typically lack the statistical power to detect small changes in mortality rates. In our larger study of 20 US cities, we did not find evidence of an overall association between heat alerts and lower mortality, nor did we find evidence of such an association in any single city other than Philadelphia.

We hypothesized that a set of city-level characteristics may explain heterogeneity in heat alert effectiveness across cities. Some of these characteristics are stable or slowly changing aspects of a city's environment and population (e.g., mean April–October heat index, percent of the population age 65 years and older), while others could be altered as part of an intervention (e.g., AC prevalence, percent of heat alerts issued as excessive heat warnings). We did not observe an association between any of these characteristics and heat alert effectiveness. However, our ability to detect associations was limited by the relatively small number of cities contributing to the meta-regression models, as well as the absence of an association between heat alerts and mortality in most cities during the study years.

Another factor that could be a determinant of heat alert effectiveness is the presence of a plan to communicate to the public about and respond to the health risks of extreme heat, beyond the messaging contained in the heat alerts themselves. While awareness of heat alerts appears to be quite high, it appears that relatively few people take action to protect their health during extreme heat events. For example, in a survey of four cities in the US and Canada, including Philadelphia, approximately 90% of participants reported being aware of heat alerts, yet in most cities fewer than 50% of participants reported changing their behavior in response to alerts (Sheridan, 2007). Thus, the implementation of heat response plans that either facilitate individual behavior change in response to heat alerts – or do not rely on individual behavior change – could have a substantial public health benefit. Among cities in this study, both Philadelphia and Washington, DC are known to have had a heat response plan in place during the study years (Sheridan and Kalkstein, 2004; HSEMA, 2001). We do not have information on the presence or absence of heat response plans in the other 18 cities; however, results from a large survey of county-level health and emergency response departments from 190 communities

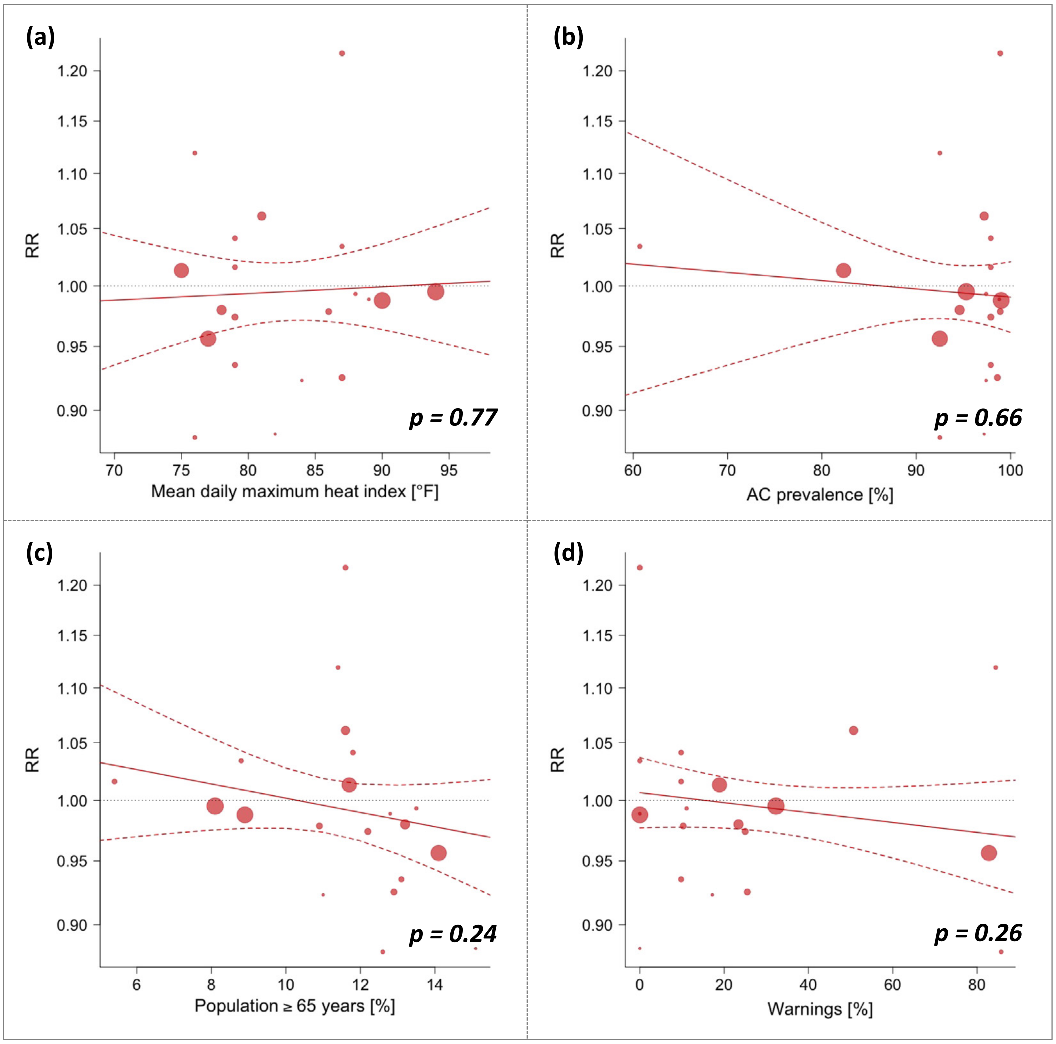

Fig. 3. Meta-regression scatterplots relating the magnitude of the association between National Weather Service heat alerts and mortality in 20 US cities, 2001–2006, with four city-level characteristics: (a) mean daily maximum heat index in April-October, (b) air conditioning prevalence, (c) percent of city residents 65 years and older, and (d) percent of heat alerts issued as excessive heat warnings.

across 30 US states suggests that the prevalence of such plans during this time period was low. Specifically, only 40% of communities in this study reported having a heat response plan as of 2011, and approximately 80% of these had implemented their plans within the six years prior to 2011 (i.e., the implementation occurred in 2005 or later) (White-Newsome et al., 2014).

Notably, we found that heat alerts in Philadelphia, which had an extensive heat response plan in place during the study years, were associated with a 4.4% (95% CI: -8.3, −0.3) reduction in the mortality rate. Activities in Philadelphia's heat response plan include ensuring continued utility service for electricity and water, providing home visits to vulnerable individuals, and increasing the number of emergency medical service personnel (Sheridan and Kalkstein, 2004). However, this study was not designed to determine whether the protective association with heat alerts observed in Philadelphia could be attributed to this heat response plan, other characteristics of the city, or chance variation. Given that we estimated the association between heat alerts and mortality in 20 cities, it is possible that the statistically significant association we observed in Philadelphia is a chance finding, the probability of which is inflated due to multiple testing. Thus, identifying the role of heat response plans as a modifier or mediator of heat alert effectiveness is a key future research direction, especially as such plans have become more common in recent years (White-Newsome et al., 2014).

Under the unverifiable assumption that the association we observed in Philadelphia reflects a causal protective effect of heat alerts, we estimate that heat alerts on eligible days in Philadelphia averted approximately 45 deaths each year during the study period. These results are similar in magnitude to those observed in a previous analysis of heat alert effectiveness in Philadelphia, in which heat alerts were estimated to have averted a total of 117 deaths among older adults between 1995 and 1998 (Ebi et al., 2004), or approximately 29 deaths per year. While our estimate of averted deaths conveys a sense of the magnitude of the public health benefit of heat alerts, it is important to keep in mind the limitations and assumptions of our approach to estimating the underlying association.

As noted already, heat alerts in the other 19 cities studied were not statistically significantly associated with lower mortality rates. However, to quantify the potential benefit of heat alerts in these other cities we projected the number of deaths that could have been potentially averted per year under the counterfactual scenario that heat alerts in these cities had been as effective as heat alerts were observed to be in Philadelphia, again assuming the observed association in Philadelphia is causal. This analysis is intended as a thought experiment to estimate the potential benefit of heat alerts on mortality in each city under the stated assumptions. We estimate that a total of 159 deaths per year could have been averted between 2001 and 2006 in the other 19 cities if this counterfactual scenario were possible to achieve. These results

Table 3
Expected annual number of deaths averted by heat alerts in Philadelphia assuming the observed association is causal, and annual number of deaths that could have potentially been averted in other cities if the heat alerts issued during eligible days in those cities had been as effective as heat alerts in Philadelphia.

City	Expected number of deaths on a day without a heat alert[a] [n/day]	Expected or potential number of deaths averted (95% eCI) per heat alert[b] [n/alert]	Mean annual number of heat alerts on eligible days [n/year]	Expected or potential number of deaths averted (95% eCI) per year given observed heat alert history [n/year][c]
Expected				
Northeast				
Philadelphia	110.6	4.8 (0.3, 9.0)	9.3	45.1 (3.1, 84.1)
Potential				
Midwest				
Kansas City, KS	26.5	1.2 (0.1, 2.2)	11.5	13.3 (0.9, 24.9)
Topeka, KS	3.8	0.2 (0.0, 0.3)	7.0	1.2 (0.1, 2.2)
Northeast				
Baltimore, MD	38.8	1.7 (0.1, 3.2)	9.2	15.5 (1.1, 29.0)
New York, NY	148.4	6.5 (0.4, 12.1)	4.2	27.0 (1.9, 50.4)
Rockville, MD	13.1	0.6 (0.0, 1.1)	9.0	5.2 (0.4, 9.6)
Trenton, NJ	6.5	0.3 (0.0, 0.5)	9.5	2.7 (0.2, 5.0)
Upper Marlboro, MD	11.5	0.5 (0.0, 0.9)	9.0	4.5 (0.3, 8.4)
Washington, DC	14.2	0.6 (0.0, 1.2)	10.5	6.5 (0.4, 12.2)
Wilmington, DE	8.2	0.4 (0.0, 0.7)	8.0	2.9 (0.2, 5.3)
Southeast				
Annandale, VA	10.8	0.5 (0.0, 0.9)	9.0	4.2 (0.3, 7.9)
Charleston, SC	7.1	0.3 (0.0, 0.6)	6.0	1.8 (0.1, 3.5)
Fayetteville, NC	5.7	0.2 (0.0, 0.5)	4.8	1.2 (0.1, 2.2)
Little Rock, AR	7.5	0.3 (0.0, 0.6)	10.2	3.3 (0.2, 6.2)
Memphis, TN	16.9	0.7 (0.1, 1.4)	6.5	4.8 (0.3, 8.9)
Monroe, LA	3.0	0.1 (0.0, 0.2)	7.5	1.0 (0.1, 1.8)
Southwest				
Dallas/Fort Worth, TX	54.5	2.4 (0.2, 4.4)	11.8	28.2 (1.9, 52.6)
Tulsa, OK	12.6	0.6 (0.0, 1.0)	8.5	4.7 (0.3, 8.7)
Phoenix, AZ	51.2	2.2 (0.2, 4.2)	12.4	27.7 (1.9, 51.8)
West				
Bakersfield, CA	13.3	0.6 (0.0, 1.1)	5.4	3.1 (0.2, 5.9)

[a] Expected number of deaths from each city-specific model for a day with no heat alert or holiday, where year = 2003, month = July, day of week = Wednesday, and heat index = the city-specific median heat index at which alerts were issued.

[b] Expected or potential number of deaths that could be averted on the days described in (a) given that a heat alert was issued and if heat alerts were as effective in all cities as they were in Philadelphia.

[c] Expected or potential mean number of deaths per year that could have been averted in each city between 2001 and 2006, if alerts were as effective as they were in Philadelphia.

suggest that the public health benefits of issuing heat alerts are potentially large, and highlight the importance of identifying the determinants of heat alert effectiveness. The role of heat alerts specifically, and adaptation to heat more broadly, is particularly important in light of the anticipated continued rise in global mean surface temperatures due to climate change. Specifically, as days of high heat become more common and intense (IPCC, 2013), improved strategies for preventing heat-related deaths will become increasingly important to minimize the adverse health impacts of climate change.

Our results should be viewed in the context of several limitations. First, as already noted, our analyses were restricted to 20 US cities that issued heat alerts during 2001–2006 and to days where the probability of observing a heat alert was > 0 but < 1. Thus, our results may not be generalizable to other cities, to more recent years, or to alerts issued on days when the heat index is very high. Second, our analyses assume that all individuals within a city are exposed to the same value of maximum heat index on any given day, an assumption that may not be met particularly in cities with pronounced variation in the impact of the urban heat island. However, our analysis should yield unbiased results if the spatial distribution of the heat index within cities remained stable across the 6-year study period. Third, while we hypothesize that the presence of a heat response plan may have contributed to alert effectiveness in Philadelphia, we do not have information on the presence of heat response plans in 18 of the 20 cities during the study period, although as discussed above, the prevalence of such plans during this time period was quite low. Additionally, while survey-based work suggests that awareness of heat alerts among the general public is high (Sheridan, 2007), we do not have information on the degree to which heat alert messaging reached the populations of the 20 cities included in this analysis. Fourth, our estimate of deaths potentially averted by heat alerts does not allow us to capture the degree to which such lives are prolonged, a relevant question given the substantial literature on mortality displacement following extreme heat events (Armstrong et al., 2017). Finally, we did not examine the impact of heat alerts on measures of morbidity, such as emergency department visits or hospitalizations, which although less severe outcomes than death, may affect many more people.

On the other hand, this study has a number of notable strengths. The format in which NWS releases heat alerts (i.e., as text files) has been cited as a challenge in prior efforts to determine their public health impact (Zhang et al., 2014). By implementing and validating a text parsing program to extract information from heat alerts, we were able to conduct an analysis of alert effectiveness on a much larger geographic scale than in previous work (Benmarhnia et al., 2016; Chau et al., 2009; Ebi et al., 2004). An additional strength of our analytic approach was the use of a case-crossover design. Because exposures are matched on the individual, this design eliminates confounding by individual characteristics that do not vary over time. Furthermore, by comparing mortality rates on days of approximately equal heat index, both with and without heat alerts, we were able to disentangle the effect of heat alerts from other factors that may vary more slowly over time and influence the relationship between heat and mortality, such as increases in air conditioning prevalence. Finally, the results of sensitivity analyses suggest that our results were robust to a number of

alternate analytic choices.

5. Conclusions

In a large study conducted across 20 US cities, we did not find evidence to support the hypothesis that NWS heat alerts issued between 2001 and 2006 reduced mortality. These results suggest that there may be an opportunity for the public health community to better leverage these alerts to protect population health during extreme heat events. Future research confirming these results and further clarifying what makes heat alerts more effective in some locations or populations than others would facilitate this important task.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.03.028.

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